Warehouse performance measurement: classification and mathematical expressions of indicators

Francielly Hedler Staudt, Maria Di Mascolo, Gülgün Alpan, Carlos M. Taboada Rodriguez

ILS2014
5th International Conference
Information Systems, Logistics and Supply Chain
August 24-27 2014
Dinalog | Beta | TRAIL | Breda, The Netherlands

Warehouse performance measurement: classification and mathematical expressions of indicators

STAUDT, F. H.[a,b]; DI MASCOLO[a], M.; ALPAN, G.[a]; RODRIGUEZ, C. M. T.[b]
[a] Univ. Grenoble Alpes, G-SCOP, F-38000 Grenoble, France
CNRS, G-SCOP, F-38000 Grenoble, France
[b] Federal University of Santa Catarina – Florianópolis, Brazil.
francielly.staudt@g-scop.grenoble-inp.fr, maria.di-mascolo@g-scop.grenoble-inp.fr ,
gulgun.alpan@grenoble-inp.fr, carlos.taboada@ufsc.br

Abstract: *Literature about warehouse performance focuses mainly on the analysis of indicator results, and less attention is given to metric definitions and measurement. This situation generates confusions in the indicator definitions, and different measurements for the same performance indicators could be made by distinct authors. In order to improve this measurement, this paper makes a synthesis of the measures found in literature to evaluate warehouse performance, defining their boundaries and equations. The indicators are classified and grouped according to the dimensions of time, quality, cost and productivity. In order to maintain consistency among metrics from different warehouse areas, a standard warehouse is defined with its layout, activities and indicators measurement units. Then, the indicator definitions found in the literature are analyzed, considering the measurement units defined in the standard warehouse, in order to state indicators with mathematical expressions. The result is a well-defined set of metrics available to companies for a more accurate warehouse management.*

Keywords: *warehouse, performance measurement, indicator, metrics.*

1 Introduction

Warehouse performance evaluation has been explored in different ways by researchers. Some of them focus on one specific area while others try to cover all warehouse activities. The performance measurement is commonly assessed by the use of indicators, present in the majority of works. However, in literature there does not exist a common understanding on the definition of these indicators and on how to measure them. Many studies are developed using indicators that are classified and measured differently in each work.

In this context, the objective of this work is to synthesize the warehouse performance indicators based on a literature review. The set of indicators noticed in papers are classified according to the dimensions of time, productivity, cost and quality. Then, the definitions found in the literature are transformed into equations, based on a standard warehouse operation.

The organization of the paper is as follows: section 2 describes the standard warehouse considered in this work, in terms of layout, activities and measurement units. After the indicator classification on time, quality, cost and productivity dimensions, indicator definitions and the related equations are given in section 3. Finally, the conclusions are presented with suggestions for future research.

2 Standard Warehouse

Warehouses can have different configurations according to the product specification, customer requirements, service level offered etc. In this work, the considered standard warehouse is shown in Figure 1. This facility supplies the market with a make-to-stock production. In a make-to-stock production, the customer orders generate a process that starts in picking activity and goes on until the product is delivered to the client. The inbound area of warehouse encompasses the receiving of trucks until the storage of products in stock area.

Figure 1 is divided in three parts: units of measure, warehouse layout, warehouse activities. Each part is explained in the next subsections.

2.1 Warehouse Layout

The middle part of Figure 1 shows the basic layout of the warehouse, with the following regions: receiving docks for inbound trucks, unloading area, inventory area, packing and shipping area, and delivery docks for shipment.

Since the majority of warehouses employ humans for order picking (De Koster et al. 2007), this warehouse follows a manual system for storage and picking products. In the manual system, the order picker/ forklift driver has to store products in a proper location (in case of storage activity) or locates the product in racks (in case of order picking).

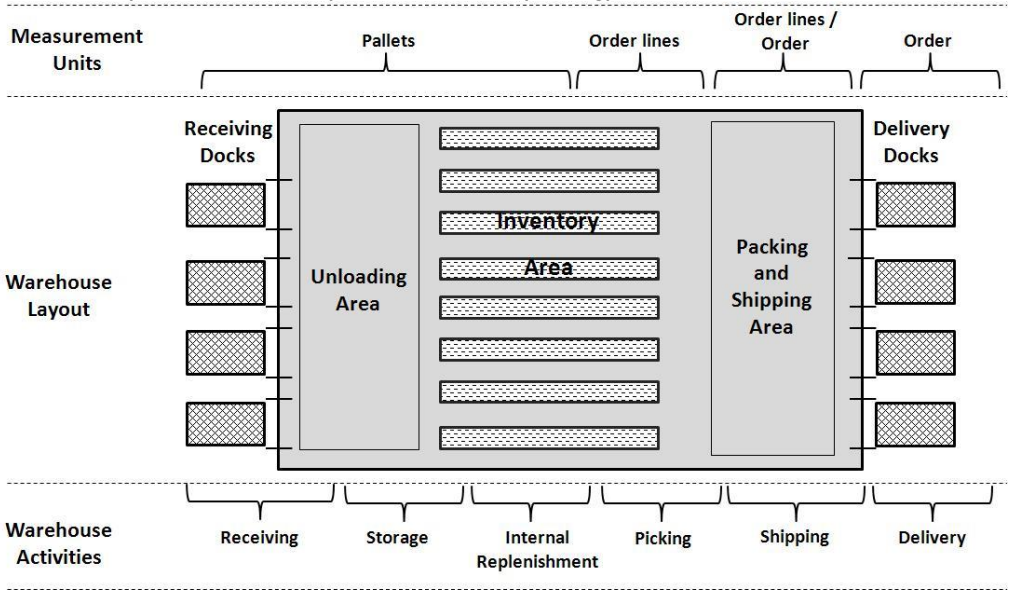

Figure 1: Standard Warehouse used in this work and its activities.

The inventory area of Figure 1 comprehends the reserve storage area and the forward picking area. The reserve area contains the bulk stock and it is located in superior rack levels. The forward picking area is located in the same racks as the bulk stock, but in the inferior levels to facilitate the order picking process. So, this configuration implies regular internal replenishments from the reserve to the forward area.

2.2 Warehouse Activities

Below the warehouse layout in Figure 1, we demonstrate the main warehouse activities with their respective boundaries: receiving, storage, internal replenishment, picking, shipping, delivery.

The activity boundaries are determined according to their definitions:
– Receiving activity: operations that involve the assignment of trucks to docks and the scheduling of unloading activities (Gu et al. 2007);
– Storage: material movement from unloaded area to its designated place in inventory (Yang & Chen 2012; Mentzer & Konrad 1991);
– Replenishment: product transfer from reserve storage area to forward pick area (Manikas & Terry 2010);
– Order Picking: process of obtaining a right amount of the right products for a set of customer orders (De Koster et al. 2007). This is the main and the most labor-intensive activity of warehouses (Dotoli et al. 2009);
– Shipping: execution of packing and truck's loading after picking, involving also the assignment of trucks to docks (Gu et al. 2007);
– Delivery: transit from the warehouse to the customer.

Here, the delivery is considered as a warehouse activity because various quality indicators take them into account as a part of warehouse performance (e.g. perfect order and on time delivery).

The inventory, i.e. the warehouse physical area in which the products remain until they are picked, is also considered as an important management part to achieve a high warehouse performance. Gallmann & Belvedere (2011) state that companies take into account inventory management as a key to reach excellent service levels.

2.3 Measurement units

The top of Figure 1 shows the measurement units used to calculate warehouse performance indicators. The units are: pallets, order lines, and orders.
A ``customer order'' or simply “order” (as described in this work) is an individual customer request to be fulfilled by the warehouse. It generally includes product types and their quantities (Johnson et al. 2010). “Order lines” are the number of different product types in a customer order. Each line designates an unique product or stock keeping unit (SKU) in a certain quantity (De Koster et al. 2007). A pallet refers to the transported product quantity on it.

Each measurement unit described in the top of Figure 1 is related to one or more warehouse activities. For example, in receiving, storage and internal replenishment, the operations are measured in “pallets”. Similarly, “order lines” is the unit for picking indicators and “order” is the standard measure for delivery indicators.

The exception is the shipping activity, where both “order lines” and “orders” are used to measure shipping indicators. Packing and shipping are transition areas, in which some indicators are related to internal operations (e.g. labor performance in shipping activity) whereas others are customer-oriented (e.g. orders shipped on time). In this work, shipping indicators also comprehend packing activities (e.g. productivity of shipping activity encompass packing and shipping labors).

3 Warehouse Performance Indicators

A literature research is carried out in order to identify the indicators utilized by authors to measure warehouse performance. The objective of this research is to synthesize indicator definitions and delimitations and transform them into measurable equations. The indicator's time base used in this work is “month” and the measurement units follow the description made in Section 2.3.

Once the set of indicators are extracted from papers, they are classified according to the dimensions of *time* (Mentzer & Konrad 1991; Neely et al. 1995; Gallmann & Belvedere 2011), *quality* (Neely et al. 1995; Frazelle 2002; Gallmann & Belvedere 2011), *cost* (Beamon 1999; Keebler & Plank 2009), and *productivity* (Frazelle 2002; Keebler & Plank 2009). We note that, for the sake of uniformity throughout this literature review, the classifications presented in this article are based on our interpretation, instead of the original category proposed by the authors. For example, Saetta et al. (2012) measure the customer satisfaction as “the percentage of orders on time”. We define customer satisfaction according to Voss et al. (2005) as “the number of customer complaints by number of orders” and measure “the percentage of orders on time” in “on time delivery” indicator. The classification results are shown in Table 1, 3, 5, 7.

After the classification, the indicator definitions are transformed into equations. While some definitions are easily expressed by equations, others need to be interpreted. Tables 1, 3, 5, 7 present three kinds of indicators, distinguished by the symbols [a], [b] and [c]. The indicators symbolized as [a] need an interpretation of their definitions to be transformed into equations. One example is the “receiving time”, defined as unloading time (see Table 1). We determine its equation as the total unloading time divided by the number of pallets unloaded per month (Equation 1). To make the performance measurement encompass all warehouse activities, the indicators not found in the literature take a definition and measurement defined by the authors. The symbol [b] represents these indicators. The symbol [c] is attributed to maintenance cost indicator (Table 5), the only metric defined by the union of two distinct definitions (papers (1) and (2)).

All others indicators, described in Table 1, 3, 5, 7 without symbols, have their measurement given directly by their definition (e.g. lead time to pick an order line, total of products stored per labor hour storing, etc.). Some of these definitions are just adjusted to the measurement unit used in this work.

For example, picking accuracy is defined as ``order picked correctly per orders picked'' but we changed the unit “order picked” to “order line picked”.

To define the data used in each indicator’s equation, Tables 2, 4, 6, 8 describe the data meanings and their measurement units (in parenthesis). Similarly, Equation 1 to Equation 40 show the indicator measurement units in parenthesis.

The next sections present the results of indicator classifications and definitions, with the related mathematical equations.

3.1 Time Indicators

Symbol	Indicator	Definition	Authors	Equation
$\mathbf{Rec_t}$	Receiving time	unloading time	Gu et al. (2007); Matopoulos and Bourlakis (2010)	(1)[a]
$\mathbf{Pu_t}$	Putaway time	lead time since a product(s) has been unloaded to when it is stored in its designated place	Mentzer and Konrad (1991); De Koster et al. (2007); Yang and Chen (2012)	(2)[a]
$\mathbf{DS_t}$	Dock to stock time	lead time from supply arrival until product is available for order picking	Ramaa et al. (2012)	(3)[a]
$\mathbf{Rep_t}$	Replenishment time	lead time to transfer products from reserve storage area to forward pick area	our definition	(4) [b]
$\mathbf{Pick_t}$	Order picking time	lead time to pick an order line	Mentzer and Konrad (1991)	(5)
$\mathbf{Ship_t}$	Shipping time	lead time to load a truck per total orders loaded	Campos (2004)	(6)
$\mathbf{Del_t}$	Delivery lead time	total time of distributions per total orders distributed	Campos (2004)	(7)
$\mathbf{OrdLT_t}$	Order lead time	lead time from customer order to customer acceptance	Mentzer and Konrad (1991); Menachof et al. (2009); Yang and Chen (2012)	(8)

Table 1: Warehouse time indicator definitions.
[a] Indicator needing interpretation to create its equation [b] Indicator definition not found in literature.

Data	Meaning
Δt (Rec)=	Time between the supply arrival and the instant when product is unloaded (*hour*)
Δt (Sto)=	Time between the instant when product is unloaded until its storage (*hour*)
Δt (DS)=	Time between the supply arrival up to product storage (*hour*)
Δt (Rep)=	Time between the transfer of products from reserve storage area to forward picking area (*hour*)
Δt (Pick)=	Time between the instants when operator starts to pick an order and when the picking finishes (*hour*)
Δt (Ship)=	Time between the instants when the order picking finishes and when the truck loading is complete (*hour*)
Δt (Del)=	Time between the truck loading and the customer acceptance of the product (*hour*)
Δt (Ord)=	Time between the customer ordering and the customer acceptance of the product (*hour*)
Pal Unlo=	number of pallets unloaded *(nb/month)*
Pal Sto	number of pallets stored *(nb/month)*
Pal Moved =	number of pallets moved during replenishment operation *(nb/month)*
Cust Orders=	number of customer orders *(nb/month)*
OrdLi Pick=	number of order lines picked *(nb/month)*
OrdLi Ship=	number of order lines shipped *(nb/month)*
Ord Del=	number of orders delivered *(nb/month)*

Table 2: Description of data related to Time indicators.

$$\mathbf{Rec_t} = \frac{\sum \Delta t(\text{Rec})}{\text{Pal Unlo}} \left(\frac{hour}{pallet}\right) \quad (1)$$

$$\mathbf{Pu_t} = \frac{\sum \Delta t(\text{Sto})}{\text{Pal Sto}} \left(\frac{hour}{pallet}\right) \quad (2)$$

$$\mathbf{DS_t} = \frac{\sum \Delta t(\text{DS})}{\text{Pal Unlo}} \left(\frac{hour}{pallet}\right) \quad (3)$$

$$\mathbf{Rep_t} = \frac{\sum \Delta t(\text{Rep})}{\text{Pal Moved}} \left(\frac{hour}{pallet}\right) \quad (4)$$

$$\mathbf{Pick_t} = \frac{\sum \Delta t(\text{Pick})}{\text{OrdLi Pick}} \left(\frac{hour}{orderline}\right) \quad (5)$$

$$\mathbf{Ship_t} = \frac{\sum \Delta t(\text{Ship})}{\text{OrdLi Ship}} \left(\frac{hour}{orderline}\right) \quad (6)$$

$$\mathbf{Del_t} = \frac{\sum \Delta t(\text{Del})}{\text{Ord Del}} \left(\frac{hour}{order}\right) \quad (7)$$

$$\mathbf{OrdLT_t} = \frac{\sum \Delta t(\text{Ord})}{\text{Ord Del}} \left(\frac{hour}{order}\right) \quad (8)$$

3.2 Productivity Indicators

Productivity can be defined as the level of asset utilization (Frazelle 2002), or how well resources are combined and used to accomplish specific, desirable results (Neely et al. 1995).

Warehouses have normally many labor-intensive activities. Bowersox et al. (2002) affirm that logistics executives are very concerned with labor performance. In fact, the number of papers found concerning this theme confirms his statement. The first two indicators of Table 3 (Labor productivity and Labor efficiency) measure the labor productivity in two different ways. The first indicator, Lab_p, measures labor productivity in terms of the number of items processed in the warehouse; the second, LE_p, measures the workers efficiency comparing the time spent to execute the tasks with the time defined by engineering. We leave to the manager the choice of the indicator that best suits his context.

Symbol	Indicator	Definition	Authors	Equation
$\mathbf{Lab_p}$	Labor productivity	ratio of the total number of items managed to the amount of item-handling working hours	De Marco and Giulio (2011)	(9)
$\mathbf{LE_p}$	Labor efficiency	standard time defined by engineering divided by actual time	Goomas et al. (2011)	(10)
$\mathbf{Rec_p}$	Receiving productivity	number of vehicles unloaded per labor hour	Mentzer and Konrad (1991)	(11)
$\mathbf{Sto_p}$	Storage productivity	total number of products stored per labor hour in storage activity	our definition	(12) [b]
$\mathbf{Rep_p}$	Replenishment productivity	total number of pallets moved per labor hour in replenishment activity	our definition	(13) [b]
$\mathbf{Pick_p}$	Picking productivity	total number of products picked per labor hours in picking activity	Kiefer and Novack (1999); Manikas and Terry (2010); Yang and Chen (2012)	(14)
$\mathbf{Ship_p}$	Shipping productivity	total number of products shipped per time period	Mentzer and Konrad (1991); Kiefer and Novack (1999); De Koster and Warffemius (2005)	(15)
$\mathbf{Del_p}$	Delivery Productivity	total number of orders delivered per labor hours in delivery activity	our definition	(16) [b]
$\mathbf{InvUt_p}$	Inventory utilization	rate of space occupied by storage	Ramaa et al. (2012); Ilies et al. (2009)	(17)
$\mathbf{TO_p}$	Turnover	ratio between the cost of goods sold and the average inventory	Johnson and McGinnis (2011); Yang and Chen (2012)	(18)
$\mathbf{TrUt_p}$	Transport utilization	vehicle fill rate	O'Neill et al. (2008); Matopoulos and Bourlakis (2010)	(19)
$\mathbf{WarUt_p}$	Warehouse utilization	rate of warehouse capacity used	Bowersox et al. (2002)	(20)
$\mathbf{EqD_p}$	Equipment downtime	percentage of hours that the equipment is not utilized	Bowersox et al. (2002)	(21)
$\mathbf{Th_p}$	Throughput	items / hour leaving the warehouse	Mentzer and Konrad (1991); Kiefer and Novack (1999); De Koster and Warffemius (2005); Gu et al. (2007)	(22)

Table 3: Warehouse productivity indicator definitions.
[b] Indicator definition not found in literature.

Data	Meaning
WH =	number of item-handling working hours *(hour/month)*
TheorH =	theoretical time that the operator should take to accomplish a task *(hour/month)*
Item Proc =	number of items managed by the warehouse (inbound and outbound)(nb/month)
WH Rec =	sum of employee labor hours working in receiving activity *(hour/month)*
WH Sto =	sum of employee labor hours working in storage activity *(hour/month)*
WH Pick =	sum of employee labor hours working in picking activity *(hour/month)*
WH Rep =	sum of employee labor hours working in replenishment activity *(hour/month)*
WH Ship =	sum of employee labor hours working in shipping activity *(hour/month)*
Pal Unlo =	number of pallets unloaded *(nb/month)*
Pal Sto =	number of pallets stored (nb/month)
Pal Moved =	number of pallets moved during replenishment operation (nb/month)
OrdLi Pick =	number of order lines picked *(nb/month)*
OrdLi Ship =	number of order lines shipped *(nb/month)*

CGoods =	$\sum$[(number of items sold)$_i$ x (cost)$_i$] *($/month)*
Ave Inv =	$\sum$[(average number of items in inventory)$_i$ x (cost)$_i$] *($/month)*
Inv CapUsed =	average space occupied by inventory *(m^3)*
Inv Cap =	total warehouse inventory capacity *(m^3)*
Ton Tr =	total of tons transported *(ton/month)*
Ton Avail =	$\sum$(ton capacity of each truck) *(ton)*
HEq Stop =	total number of hours during which equipments are stopped *(hour/month)*
HEq Avail =	total number of hours during which equipments are available to work *(hour/month)*
War CapUsed =	average space occupied in the warehouse *(m^3)*
War Cap =	total warehouse capacity *(m^3)*
War WH =	total number of hours during which the warehouse works *(hour/month)*

Table 4: Description of data related to Productivity indicators.

$$\mathbf{Lab_p} = \frac{\text{Item Proc}}{\text{WH}}\left(\frac{items}{LaborHour}\right) \quad (9)$$

OR

$$\mathbf{LE_p} = \frac{\text{TheorH}}{\text{WH}}(\%) \quad (10)$$

$$\mathbf{Rec_p} = \frac{\text{Pal Unlo}}{\text{WH Rec}}\left(\frac{pallets}{LaborHour}\right) \quad (11)$$

$$\mathbf{Sto_p} = \frac{\text{Pal Sto}}{\text{WH Sto}}\left(\frac{pallets}{LaborHour}\right) \quad (12)$$

$$\mathbf{Rep_p} = \frac{\text{Pal Moved}}{\text{WH Rep}}\left(\frac{pallets}{LaborHour}\right) \quad (13)$$

$$\mathbf{Pick_p} = \frac{\text{OrdLi Pick}}{\text{WH Pick}}\left(\frac{orderline}{LaborHour}\right) \quad (14)$$

$$\mathbf{Ship_p} = \frac{\text{OrdLi Ship}}{\text{WH Ship}}\left(\frac{orderline}{LaborHour}\right) \quad (15)$$

$$\mathbf{Del_p} = \frac{\text{Ord Del}}{\text{WH Del}}\left(\frac{order}{LaborHour}\right) \quad (16)$$

$$\mathbf{InvUt_p} = \frac{\text{Inv CapUsed}}{\text{Inv Cap}}(\%) \quad (17)$$

$$\mathbf{TO_p} = \frac{\text{CGoods}}{\text{Ave Inv}}\left(\frac{times}{month}\right) \quad (18)$$

$$\mathbf{TrUt_p} = \frac{\text{Ton Tr}}{\text{Ton Avail}}(\%) \quad (19)$$

$$\mathbf{WarUt_p} = \frac{\text{War CapUsed}}{\text{War Cap}}(\%) \quad (20)$$

$$\mathbf{EqD_p} = \frac{\sum \text{HEq Stop}}{\sum \text{HEq Avail}}(\%) \quad (21)$$

$$\mathbf{Th_p} = \frac{\text{Ord Ship}}{\text{War WH}}\left(\frac{items}{hour}\right) \quad (22)$$

3.3 Cost Indicators

The number of cost indicators used for warehouse management is not as abundant in the literature as the quality or the productivity indicators. Gunasekaran & Kobu (2007) confirm this fact stating that despite the strategic importance in the supply chain, warehouses have most of their activities in the operational level, which is normally based on non-financial indicators. Also, some warehouse objectives are difficult to be measured monetarily (lead-time reduction, quality improvements and customer service). For these reasons, we have not created new cost indicators related to all warehouse activities as we made in quality, time and productivity dimensions.

Symbol	Indicator	Definition	Authors	Equation
$\mathbf{Inv_c}$	Inventory costs	holding cost and the stock out penalty	Li et al. (2009)	(23)[a]
$\mathbf{Tr_c}$	Transportation costs	number of dollars spent per order delivered.	Bowersox et al. (2002)	(24)
$\mathbf{OrdProc_c}$	Order processing cost	total processing cost of all orders per number of orders	Campos (2004)	(25)
$\mathbf{CS_c}$	Cost as a % of sales	total warehousing cost as a percent of total company sales	Bowersox et al. (2002); Ilies et al. (2009); Ramaa et al. (2012)	(26)
$\mathbf{Lab_c}$	Labor cost	cost of personnel involved in warehouse operations	Cagliano et al. (2011)	(27)
$\mathbf{Maint_c}$	Maintenance cost	costs of building maintenance (1) and equipment maintenance (2)	(1)- De Marco and Giulio (2011) (2)- Johnson et al. (2010)	(28)[c]

Table 5: Warehouse cost indicator definitions.

[a] Indicator needing interpretation to create its equation [c] Indicator is the union of two paper definitions.

Data	Meaning
InvC =	financial cost to maintain warehouse inventory ($)
LostC =	penalty measured by company as a cost when the customer makes an order and the product is not available ($)
TrC=	transportation cost, which is the sum of assets, oil, maintenance and labor costs ($/month)
Ord Del =	number of orders delivered (nb/month)
Ord ProcC =	sum of office and employee costs to process orders ($)
Cust Ord =	number of customer orders (nb/month)
WarC =	sum of all activity costs that the warehouse has in charge ($)
Sales=	total of revenues from sales ($)
Salary =	salaries of all warehouse employees ($)
Charges =	charges paid for all employees ($)
BuildC =	cost to maintain warehouse building ($/month)
EqMaintC =	equipment maintenance costs ($/month)
Others =	other costs not defined in the formulas ($/month)

Table 6: Description of data used to calculate Cost indicators.

$$\mathbf{Inv_c} = \mathsf{InvC} + \mathsf{LostC}(\$) \quad (23)$$

$$\mathbf{Tr_c} = \frac{\mathsf{TrC}}{\mathsf{Ord\ Del}}\left(\frac{\$}{order}\right) \quad (24)$$

$$\mathbf{OrdProc_c} = \frac{\mathsf{Ord\ ProcC}}{\mathsf{Cust\ Ord}}\left(\frac{\$}{order}\right) \quad (25)$$

$$\mathbf{CS_c} = \frac{\mathsf{WarC}}{\mathsf{Sales}}(\%) \quad (26)$$

$$\mathbf{Lab_c} = \mathsf{Salary} + \mathsf{Charges} + \mathsf{Others}\left(\frac{\$}{month}\right) \quad (27)$$

$$\mathbf{Maint_c} = \mathsf{BuildC} + \mathsf{EqMaintC} + \mathsf{Others}\left(\frac{\$}{month}\right) \quad (28)$$

3.4 Quality Indicators

The quality indicators can be divided in two groups: some metrics are related to internal quality operations, whereas others focus on customer service level.

The “on time delivery” and the “perfect order” are related indicators because they have the same data in their equations, i.e. orders delivered on time. As perfect order is more global and the information contained in the “on time delivery” indicator is very important to the warehouse management, we do not consider them as a duplicity. Both metrics could be kept in the indicator set.

Symbol	Indicator	Definition	Authors	Equation
$\mathbf{Rec_q}$	Receiving accuracy	pallets unloaded without incidents	our definition	(29)[b]
$\mathbf{Sto_q}$	Storage accuracy	storing products in proper locations	Voss et al. (2005); Rimiene (2008)	(30)[a]
$\mathbf{Rep_q}$	Replenishment accuracy	correct movement of products from storage area to forward pick area	our definition	(31)[b]
$\mathbf{Inv_q}$	Physical inventory accuracy	the physical counts of inventory agree with the inventory status reported in the database	Bowersox et al. (2002)	(32)[a]
$\mathbf{Pick_q}$	Picking accuracy	number of orders picked correctly per orders picked	Bowersox et al. (2002)	(33)[a]
$\mathbf{Ship_q}$	Orders shipped accuracy	number of errors free orders shipped	De Koster and Warffemius (2005); De Koster and Balk (2008)	(34)[a]
$\mathbf{Del_q}$	Delivery accuracy	number of orders distributed without incidents	Campos (2004)	(35)[a]
$\mathbf{OTDel_q}$	On time delivery	number of orders received on or before committed date	Voss et al. (2005); Forslund and Jonsson (2010); Lu and Yang (2010); Yang and Chen (2012)	(36)
$\mathbf{OTShip_q}$	Orders shipped on time	number of orders shipped on time per total orders shipped	Kiefer and Novack (1999)	(37)
$\mathbf{OrdF_q}$	Order fill rate	number of orders filled completely on the first shipment	Ramaa et al. (2012)	(38)
$\mathbf{PerfOrd_q}$	Perfect order	number of orders delivered on time, without damage and with accurate documentation	Kiefer and Novack (1999)	(39)
$\mathbf{CustSat_q}$	Customer satisfaction	number of customer complaints per number of orders	Lao et al. (2011); Voss et al. (2005); Lao et al. (2012)	(40)
$\mathbf{StockOut_q}$	Stockout rate	number of stock products out of order	Lao et al. (2011); Yang and Chen (2012); Lao et al. (2012)	(41)[a]

Table 7: Warehouse quality indicator definitions.
[a] Indicator needing interpretation to create its equation [b] Indicator definition not found in literature.

Data	Meaning
Cor Unlo =	number of unloading pallets occurred without incidents (nb/month)
Prob data =	number of pallets with inaccuracies between the physical inventory and the system (nb/month)
Cor Sto =	number of pallets stored in proper location (nb/month)
Cor Pick =	number of order lines picked with the right products and the right quantity (nb/month)
Cor Rep =	number of pallets moved to forward storage area correctly (nb/month)
Cor Ship =	number of order lines packed with the right products and the right quantity and shipped in the right truck (nb/month)
Cor Del =	number of orders delivered with the right products and the right quantity to the right customer (nb/month)
Pal Unlo =	number of pallets unloaded (nb/month)
Pal Sto =	number of pallets stored (nb/month)
Pal Moved =	number of pallets moved during replenishment operation (nb/month)
OrdLi Pick =	number of order lines picked (nb/month)
OrdLi Ship =	number of order lines shipped (nb/month)
Ord Ship =	number of order shipped (nb/month)
Ord Del =	number of orders delivered (nb/month)
Ord Del OT =	number of orders received by customer on or before deadline (nb/month)
Ship OT=	number of orders shipped on or before the deadline (nb/month)
Complet 1st Ship =	number of orders delivered complete on first shipment (nb/month)
Ord OT, ND, CD =	number of orders received by customer on time (OT), with no damages (ND) and correct documentation (CD) (nb/month)
Item Out =	sum of the items processed by the warehouse with items in process in picking and shipping activities (nb/month)
Cust Complain=	number of customer complaints regarding on logistics aspects (nb/month)
Item noAvail=	number of products that are not available in stock when the customer makes an order (nb/month)

Table 8: Description of data related to Quality indicators.

$$\mathbf{Rec_q} = \frac{\text{Cor Unlo}}{\text{Pal Unlo}}(\%) \quad (29)$$

$$\mathbf{Sto_q} = \frac{\text{Cor Sto}}{\text{Pal Sto}}(\%) \quad (30)$$

$$\mathbf{Rep_q} = \frac{\text{Cor Rep}}{\text{Pal Moved}}(\%) \quad (31)$$

$$\mathbf{Inv_q} = \frac{\text{(Unlo + Sto + Moved Pal) - Prob data}}{\text{Unlo + Sto + Moved Pal}}(\%) \quad (32)$$

$$\mathbf{Pick_q} = \frac{\text{Cor OrdLi Pick}}{\text{OrdLi Pick}}(\%) \quad (33)$$

$$\mathbf{Ship_q} = \frac{\text{Cor OrdLi Ship}}{\text{OrdLi Ship}}(\%) \quad (34)$$

$$\mathbf{Del_q} = \frac{\text{Cor Del}}{\text{Ord Del}}(\%) \quad (35)$$

$$\mathbf{OTDel_q} = \frac{\text{Ord Del OT}}{\text{Ord Del}}(\%) \quad (36)$$

$$\mathbf{OTShip_q} = \frac{\text{Ship OT}}{\text{Ord Ship}}(\%) \quad (37)$$

$$\mathbf{OrdF_q} = \frac{\text{Complet 1st Ship}}{\text{Ord Ship}}(\%) \quad (38)$$

$$\mathbf{PerfOrd_q} = \frac{\text{(Ord OT, ND, CD)}}{\text{Ord Del}}(\%) \quad (39)$$

$$\mathbf{CustSat_q} = \frac{\text{Cust Complain}}{\text{Ord Del}}(\frac{complains}{order}) \quad (40)$$

$$\mathbf{StockOut_q} = \frac{\text{Item noAvail}}{\text{Item Out}}(\%) \quad (41)$$

4 Conclusion

The indicators are essential for performance analysis. In the context of warehouses and distribution centers, the literature has been focusing mainly on the analysis of indicator results. As a result, there does not exist a common definition of these indicators and how to measure them. This work tries to improve this subject making a synthesis of the measures found in literature to evaluate warehouse performance, defining their boundaries and equations.

A literature review is carried out and the set of indicators found in papers are classified according to the dimensions of time, productivity, cost and quality. To transform the indicator definitions in equations, a standard warehouse is created and its layout, activities and measurement units are

defined. In order to maintain consistency among activity indicators, some definitions not found in the literature are created by the authors. The result is a set of 41 indicators available to companies for a better warehouse management.
For future research, the set of equations proposed can be evaluated in terms of their relationships, helping the manager to analyze the global performance.

5 References

Beamon, B.M., 1999. Measuring supply chain performance. International Journal of Operations & Production Management, 19(3), pp.275–292.

Bowersox, D.J., Closs, D.J. & Cooper, M.B., 2002. Supply Chain Logistics Management first edit., Michigan State University: McGraw-Hill.

Dotoli, M., Fanti, M.P., Iacobellis, G., Stecco, G., Ukovich, W., 2009. Performance analysis and management of an Automated Distribution Center. In 2009 35th Annual Conference of IEEE Industrial Electronics. Porto: IEEE, pp. 4371–4376.

Frazelle, E., 2002. World-Class warehousing and material handling 1st editio., USA: McGraw-Hill.

Gallmann, F. & Belvedere, V., 2011. Linking service level, inventory management and warehousing practices: A case-based managerial analysis. Operations Management Research, 4(1-2), pp.28–38.

Gu, J., Goetschalckx, M. & McGinnis, L.F., 2007. Research on warehouse operation: A comprehensive review. European Journal of Operational Research, 177(1), pp.1–21.

Gunasekaran, A. & Kobu, B., 2007. Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995–2004) for research and applications. International Journal of Production Research, 45(12), pp.2819–2840.

Johnson, A., Chen, W.-C. & McGinnis, L.F., 2010. Large-scale Internet benchmarking: Technology and application in warehousing operations. Computers in Industry, 61(3), pp.280–286.

Keebler, J.S. & Plank, R.E., 2009. Logistics performance measurement in the supply chain: a benchmark. Benchmarking: An International Journal, 16(6), pp.785–798.

De Koster, R., Le-Duc, T. & Roodbergen, K.J., 2007. Design and control of warehouse order picking: A literature review. European Journal of Operational Research, 182(2), pp.481–501.

Manikas, I. & Terry, L.A., 2010. A case study assessment of the operational performance of a multiple fresh produce distribution centre in the UK. British Food Journal, 112(6), pp.653–667.

Mentzer, J.T. & Konrad, B.P., 1991. An Efficiency/Effectiveness approach to logistics performance analysis. Journal of Business Logistics, 12(1), pp.33–61.

Neely, A., Gregory, M. & Platts, K., 1995. Performance measurement system design: A literature review and research agenda. International Journal of Operations & Production Management, 15(4), pp.80–116.

Saetta, S., Paolini, L., Tiacci, L., Altiok, T., 2012. A decomposition approach for the performance analysis of a serial multi-echelon supply chain. International Journal of Production Research, 50(9), pp.2380–2395.

Voss, M.D., Calantone, R.J. & Keller, S.B., 2005. Internal service quality: Determinants of distribution center performance. International Journal of Physical Distribution & Logistics Management, 35(3), pp.161–176.

Yang, L.R. & Chen, J.H., 2012. Information systems utilization to improve distribution center performance: From the perspective of task characteristics and customers. Advances in Information Sciences and Service Sciences, 4(1), pp.230–238.